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Resonances in Collection Grids of Offshore Wind Farms

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Resonances in Collection Grids of Offshore Wind Farms

Danish Wind Power Research 2013

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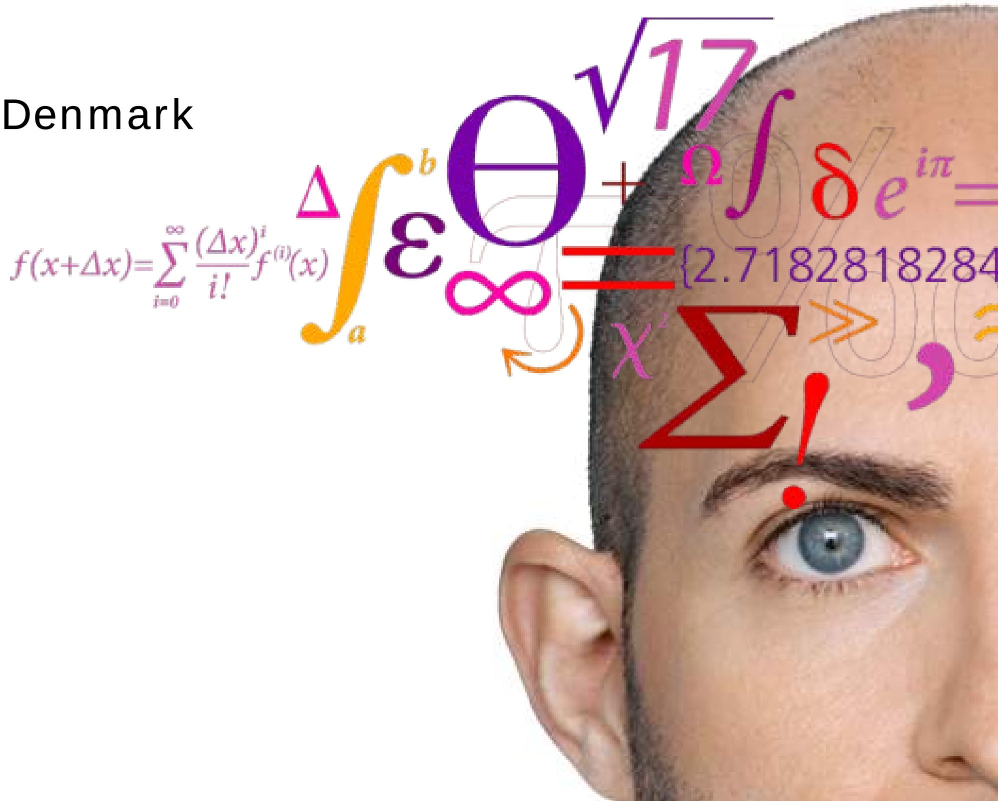


Outline

- Introduction to PhD project
- Resonance
- Example: Electrical environment of an OWF
- Wide frequency band models of components
- Is transformer properly tested? FDSF

Introduction to PhD project

Compatibility of Electrical Main Components in Wind Turbines

- To establish technical and scientific **methods and tools** for characterizing wind farm's electrical main **components and their interaction**, taking into account external **electrical conditions**, environmental aspects, operational conditions and others.

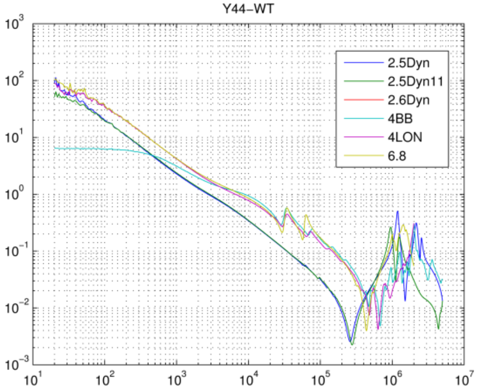
- These tools should ensure the electrical compatibility of main components with each other (component compatibility) and with environment (system compatibility). The created guidelines should be general, not limited to one specific design concept or manufacturer.

- In order to identify risky combinations, a **large number of simulations** have to be conducted under systematic parameter variation.

Introduction to PhD project

- Described and validated a method to perform wide band measurements of electric power components with commercial sweep frequency response analyzer.

- Performed wide band measurements of wind farm transformers, reactors and filters.



- Creation and validation of black box model of power transformer with a Vector Fitting algorithm and passivity enforcement.

- Implementation of parametric variation method for ATP-EMTP using Matlab.

- Describe electrical environment of OWF.

- Assumptions: wide band if possible (reality: >5kH && <1-2MHz), linear

Resonances

- **Stationary resonance:**
  - Sustained amplification of voltage or current in an electric circuit where the natural frequency of the circuit coincides with the frequency of the ideal source.
    - Very low resonance frequency of a network
    - Harmonics as a stationary source
- **Identification of resonances:**
  - Admittance / impedance sweep at chosen nodes of a network
    - Electromagnetic transient programs determine the frequency response of the network's driving-point admittance as seen from a specific node by connecting to it a sinusoidal voltage source with amplitude of one volt and measuring the current flowing into the network. The driving point admittance is proportional to the measured current.

Resonances

- **Series resonance** (or resonance)
  - Series resonance occurs when low impedance is seen at resonant frequency , which causes high current and high voltage distortion even at a location with no or little harmonic emission.
  - The series combination of the transformer inductance and capacitor bank is very small and only limited by its resistance.

- **Parallel resonance** (or anti-resonance)
  - Parallel resonance occurs when the reactance of inductive elements that is in parallel with the reactance of capacitive elements cancel each other out. Harmonic voltage experienced at the bus is amplified due to the high impedance.

Example:
Electrical environment of a an OWF

25 x 3.6MW variable speed wind turbines equipped with a full scale power converter and induction generator

Onshore substation contains:

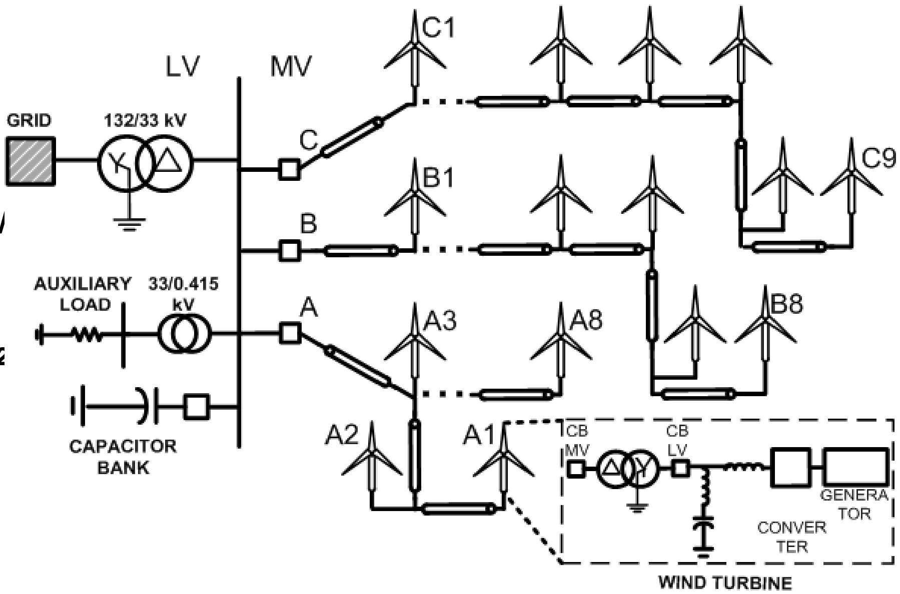
- transformer (**90MVA,132/33kV, YNd1**)
- capacitor bank (12MVAr, 33kV),
- auxiliary transformer (100kVA, 33/0.4kV) which supplies an auxiliary load of 80kW at 0.4kV.

Each radial is made of XLPE cables of diameters: **800mm², 500mm², 240mm² and 95mm²**.

The distance between the turbines is **700m** and between radials is **800m**.

Each wind turbine contains:

- wind turbine transformer (**4MVA 0.69/34kV Dyn11**)
- high frequency filter and an auxiliary load on the 0.69kV side.



Wind farm model: ATP-EMTP and ATPDraw

The 132kV Export system:

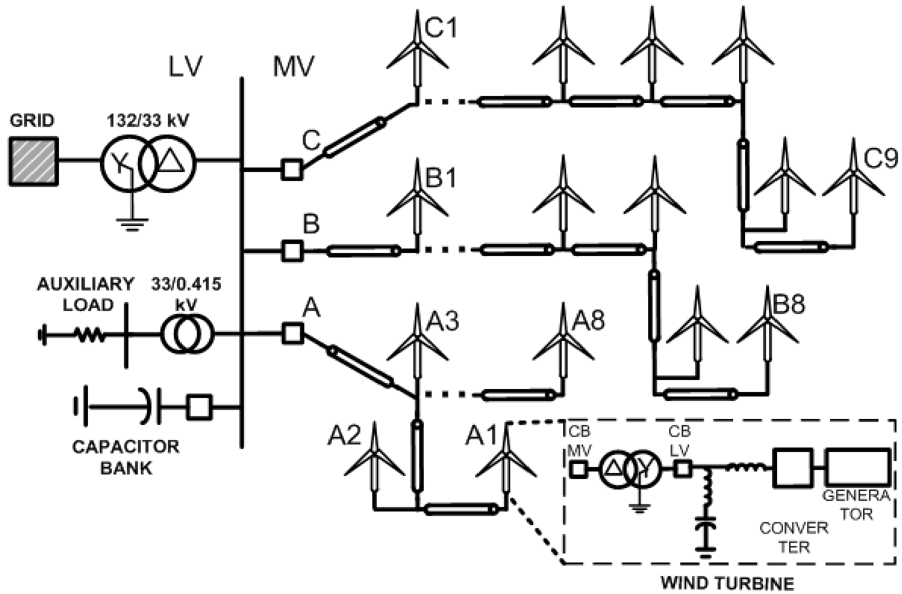
- Equivalent Thevenin voltage source with 1570MVA three phase fault capacity with an X/R ratio of 8

Transformers:

- Wind park transformer: BCTRAN (RL model based on open- and short circuit data. No core nonlinearities.)
- Wind turbine transformer:
- XFMR, basic 50Hz model with externally modelled core nonlinearities (for validation). Capacitances added for wind turbine transformers.

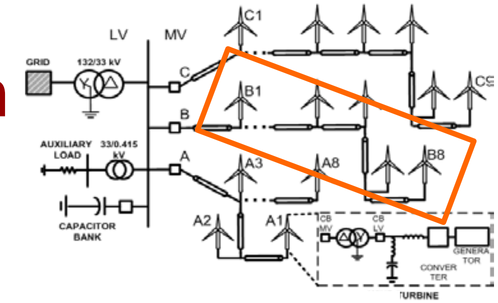
Capacitor bank modelled as lump capacitance

Busbars modelled as ideal components

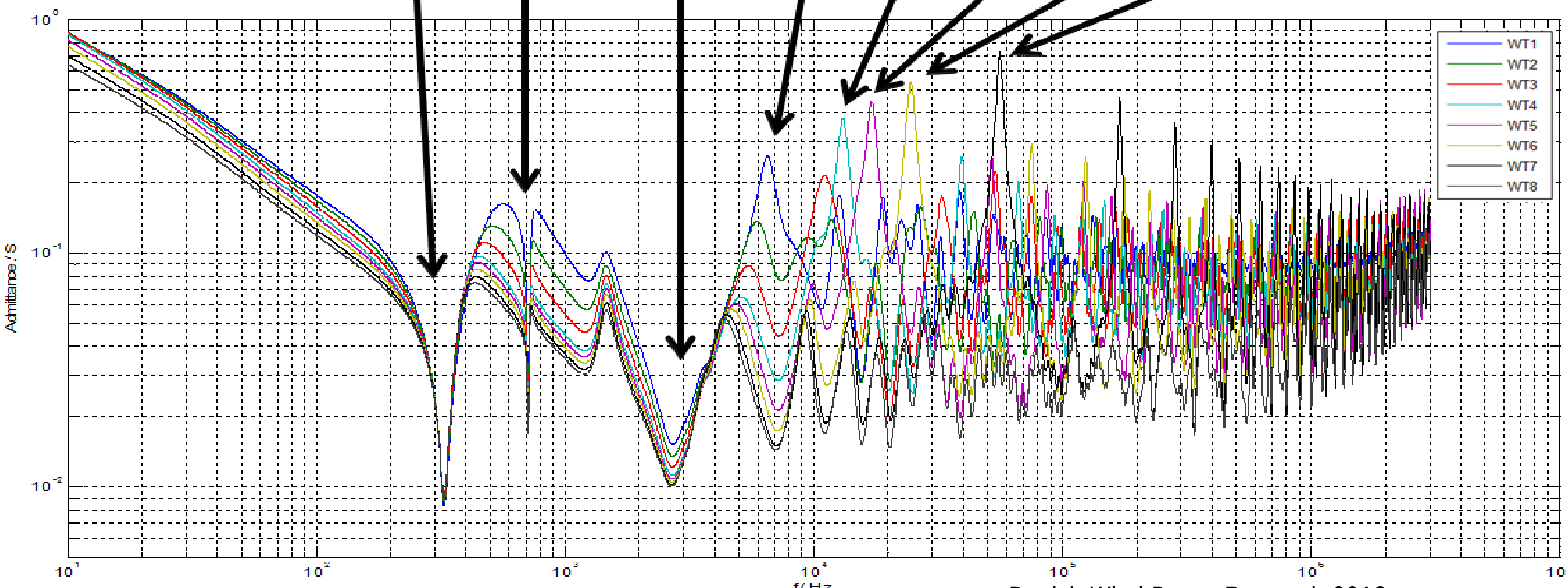


[2]A. Holdyk, I. Arana, J. Holboell, 'Switching Operation Simulations In A Large Offshore Wind Farm With Use Of Parametric Variation And Frequency Domain Severity Factor'

Electrical environment in wind farm collection grid



Peak	1p	2p	3p	4p	5p	6p	7p	8p
Frequency range (ELF-EHF)	ULF	ULF	ULF	VLF	VLF	VLF	VLF	LF
f / kHz	0.33	0.715	2.75	6.8	13.12	16.98	24.66	56.23
Resonance / anti-resonance	anti	anti	anti	res	res	res	res	res
Dominant components	WT transformer and cables	grid impedance	substation components	cable lengths	cable lengths	cable lengths	cable lengths	cable lengths
Dependent on	Most components	C bank and X/R ratio	Meas. location	Meas. location	Meas. location	Meas. location	Meas. location	Meas. location
Description	First peak	Second peak	Third peak	WT1 peak	WT4 peak	WT5 peak	WT6 peak	WT7 peak



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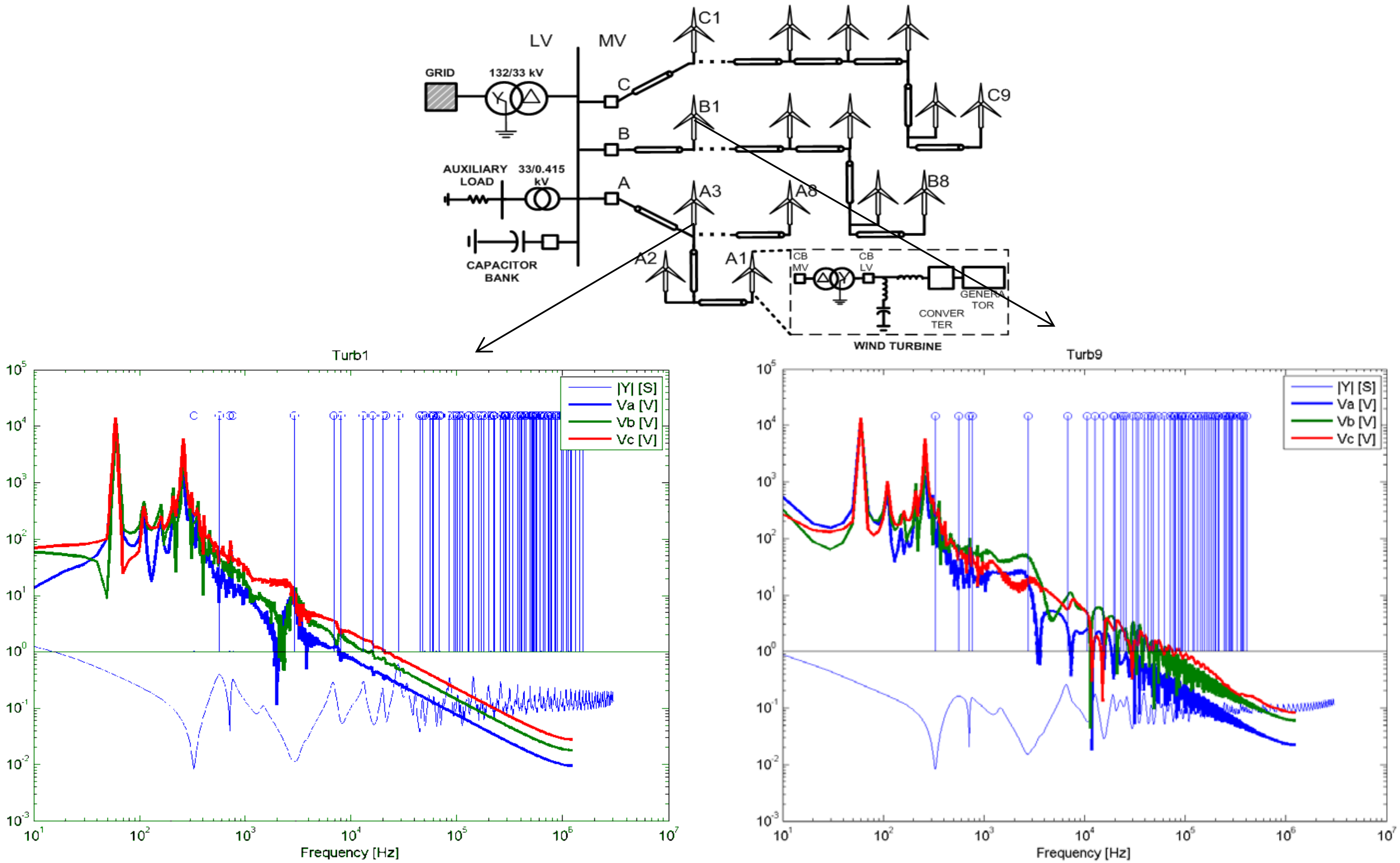
From: [1] V. Kersiulis, A. Holdyk, J. Holboell, I. Arana,‘ Sensitivity of Nodal Admittances in an Offshore Wind Power Plant to Parametric Variations in the Collection Grid

Admittance vs voltage amplification



Wide band models of components

A black box model of a transformer can be formulated using the relationship between terminal voltages *V(s)* and currents *I(s)* in frequency domain ($s=j\omega$):

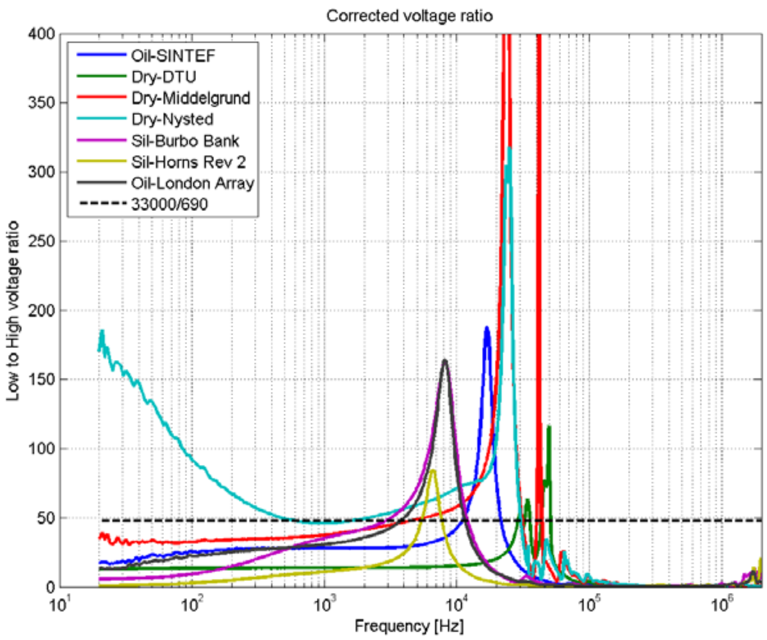
$$I(s) = Y(s) \cdot V(s)$$

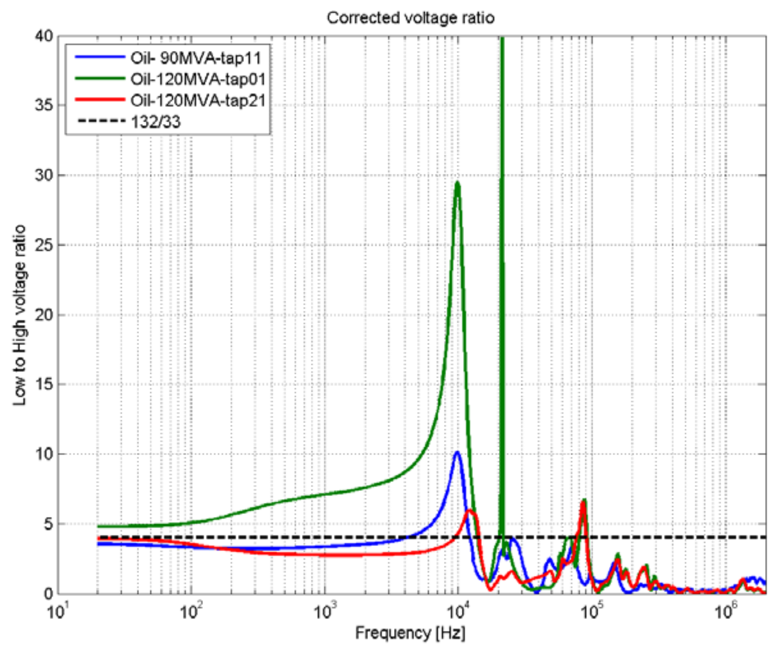
For a transformer with n terminals with ground as reference, the admittance matrix will have $n \cdot n$ elements

$$\begin{bmatrix} I_1(s) \\ \dots \\ I_i(s) \\ I_j(s) \\ \dots \\ I_n(s) \end{bmatrix} = \begin{bmatrix} Y_{11}(s) & \dots & Y_{1i}(s) & Y_{1j}(s) & \dots & Y_{1n}(s) \\ \dots & \dots & \dots & \dots & \dots & \dots \\ Y_{i1}(s) & \dots & Y_{ii}(s) & Y_{ij}(s) & \dots & Y_{in}(s) \\ Y_{j1}(s) & \dots & Y_{ji}(s) & Y_{jj}(s) & \dots & Y_{jn}(s) \\ \dots & \dots & \dots & \dots & \dots & \dots \\ Y_{n1}(s) & \dots & Y_{ni}(s) & Y_{nj}(s) & \dots & Y_{nn}(s) \end{bmatrix} \begin{bmatrix} U_1(s) \\ \dots \\ U_i(s) \\ U_j(s) \\ \dots \\ U_n(s) \end{bmatrix}$$

Resonances in transformers

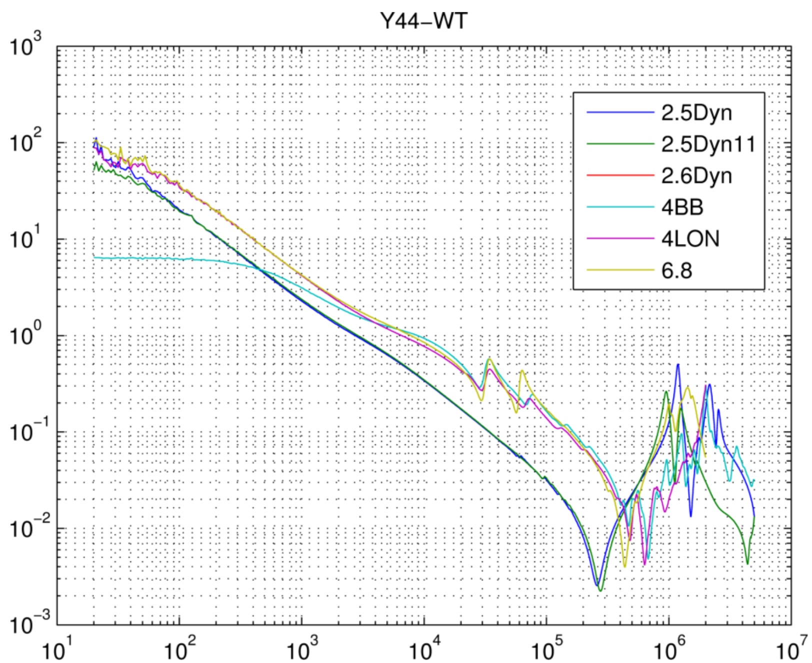
- 6 wind turbine transformers measured
- 3 wind farm transformers measured
- Positive sequence voltage ratio resonances: several kHz!

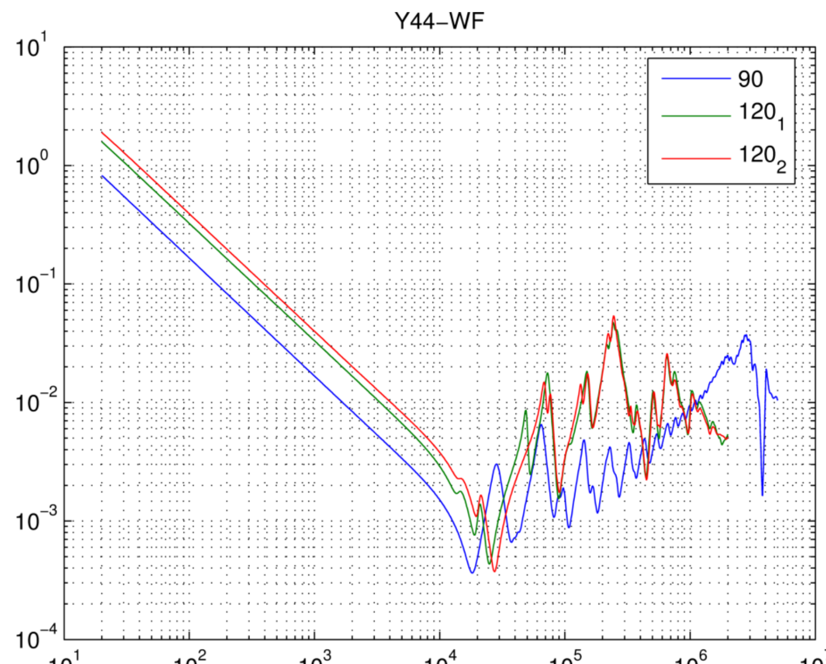




Resonances at transformer terminals

$$\begin{bmatrix} I_1(s) \\ \dots \\ I_3(s) \\ I_4(s) \\ \dots \\ I_6(s) \end{bmatrix} = \begin{bmatrix} Y_{11}(s) & \dots & Y_{13}(s) & Y_{14}(s) & \dots & Y_{16}(s) \\ \dots & \dots & \dots & \dots & \dots & \dots \\ Y_{31}(s) & \dots & Y_{33}(s) & Y_{34}(s) & \dots & Y_{36}(s) \\ Y_{41}(s) & \dots & Y_{43}(s) & \boxed{Y_{44}(s)} & \dots & Y_{46}(s) \\ \dots & \dots & \dots & \dots & \dots & \dots \\ Y_{61}(s) & \dots & Y_{63}(s) & Y_{64}(s) & \dots & Y_{66}(s) \end{bmatrix} \begin{bmatrix} U_1(s) \\ \dots \\ U_3(s) \\ U_4(s) \\ \dots \\ U_6(s) \end{bmatrix}$$





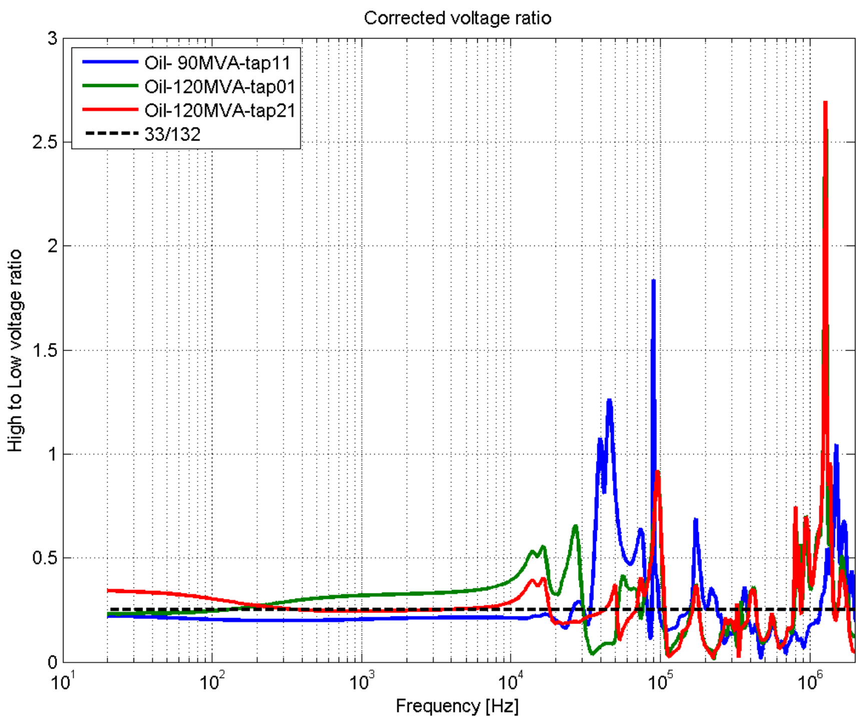
Resonances in transformers

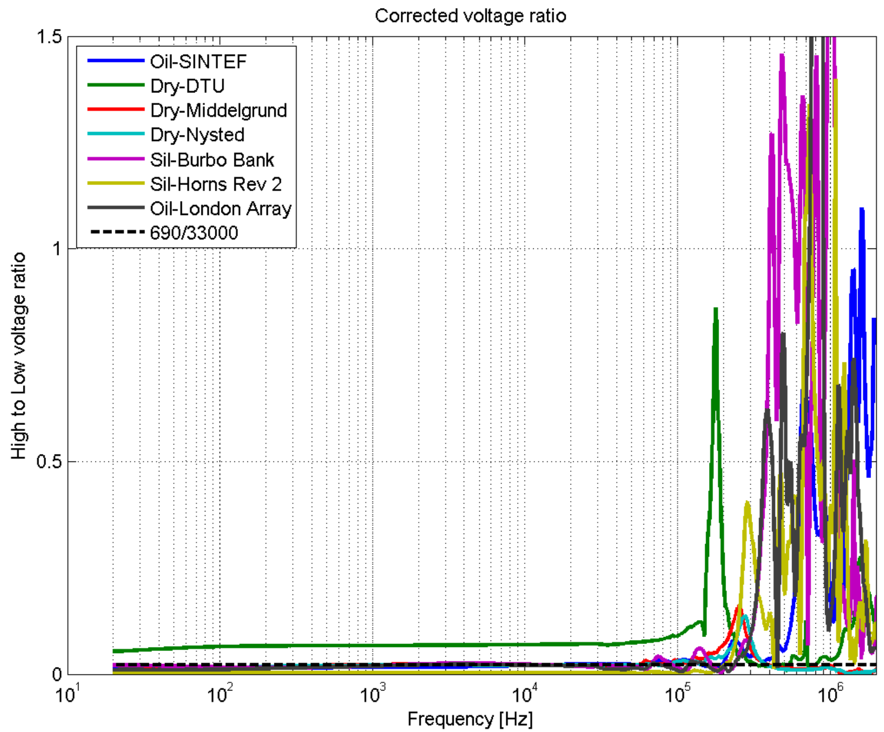
$$\begin{bmatrix} I_1(s) \\ \cdots \\ I_3(s) \\ I_4(s) \\ \cdots \\ I_6(s) \end{bmatrix} = \begin{bmatrix} Y_{11}(s) & \cdots & Y_{13}(s) & Y_{14}(s) & \cdots & Y_{16}(s) \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ Y_{31}(s) & \cdots & Y_{33}(s) & Y_{34}(s) & \cdots & Y_{36}(s) \\ Y_{41}(s) & \cdots & Y_{43}(s) & Y_{44}(s) & \cdots & Y_{46}(s) \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ Y_{61}(s) & \cdots & Y_{63}(s) & Y_{64}(s) & \cdots & Y_{66}(s) \end{bmatrix} \begin{bmatrix} U_1(s) \\ \cdots \\ U_3(s) \\ U_4(s) \\ \cdots \\ U_6(s) \end{bmatrix}$$

$$\begin{bmatrix} I_H \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{HH} & Y_{HL} \\ Y_{LH} & Y_{LL} \end{bmatrix} \cdot \begin{bmatrix} V_H \\ V_L \end{bmatrix}$$

$$V_{HL} = -Y_{HH}{}^{-1} Y_{HL}$$

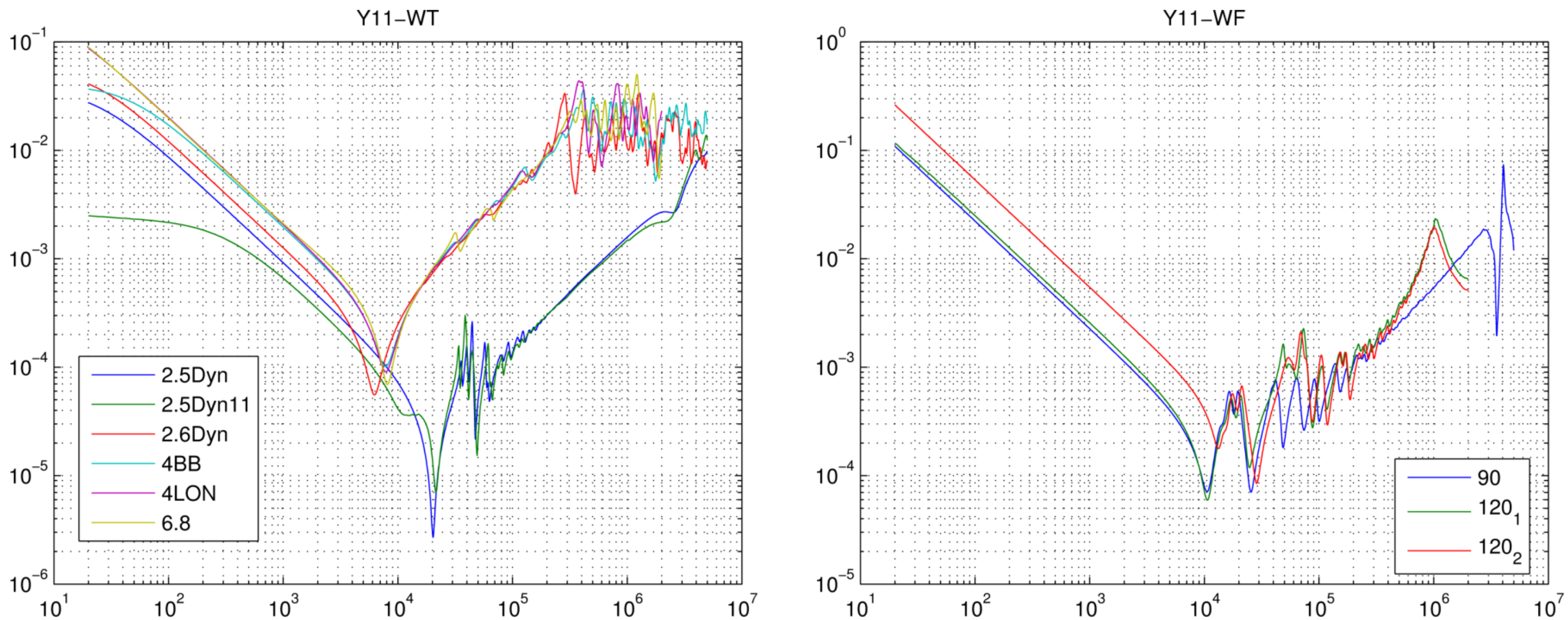
$$V_{LH} = -Y_{LL}{}^{-1} Y_{LH}$$





Resonances in transformers

- $$\begin{bmatrix} I_1(s) \\ \dots \\ I_3(s) \\ I_4(s) \\ \dots \\ I_6(s) \end{bmatrix} = \begin{bmatrix} \boxed{Y_{11}(s)} & \dots & Y_{13}(s) & Y_{14}(s) & \dots & Y_{16}(s) \\ \dots & \dots & \dots & \dots & \dots & \dots \\ Y_{31}(s) & \dots & Y_{33}(s) & Y_{34}(s) & \dots & Y_{36}(s) \\ Y_{41}(s) & \dots & Y_{43}(s) & Y_{44}(s) & \dots & Y_{46}(s) \\ \dots & \dots & \dots & \dots & \dots & \dots \\ Y_{61}(s) & \dots & Y_{63}(s) & Y_{64}(s) & \dots & Y_{66}(s) \end{bmatrix} \begin{bmatrix} U_1(s) \\ \dots \\ U_3(s) \\ U_4(s) \\ \dots \\ U_6(s) \end{bmatrix}$$



Are resonances in transformers dangerous?

- Many distribution and transmission transformers lost in Brazil in 90’s
- Joint Work Group JWG A2/C4-03. Interaction Between Transformers and the Electrical System with Focus on High Frequency Electromagnetic Transients. Finished
- Working Group A2–C4.39. Electrical Transient Interaction Between Transformers And The Power System, Finishing.

Frequency Domain Severity Factor (FDSF)

- Introduced by Cigré-Brazil Joint Working Group A2/C4-03

- Ratio between the spectral density of the calculated transient voltage and the spectral density of the envelope defined by the standard waveforms used for testing transformers

$$FDSF = \frac{\mathrm{FFT(waveform\ at\ the\ transformer\ terminal)}}{\mathrm{FFT(transformer\ test\ waveforms)}}$$

- Takes into account the frequency content of the transient voltage waveform present at transformer terminals and compares it to the frequency content of voltage waveforms for which the transformer had been tested

- Should be less than 1 to ensure that the stresses arising from a particular event occurring in the system will be adequately covered by dielectric tests performed in the laboratory.

[2] A. Holdyk, I. Arana, J. Holboell, 'Switching Operation Simulations In A Large Offshore Wind Farm With Use Of Parametric Variation And Frequency Domain Severity Factor'

Thank you for your attention

References:

[1] V. Kersiulis, A. Holdyk, J. Holboell, I. Arana,‘ Sensitivity of Nodal Admittances in an Offshore Wind Power Plant to Parametric Variations in the Collection Grid’, Proceedings of the 11th International Workshop on Large-Scale Integration of Wind Power into Power Systems. 2012

[2]A. Holdyk, I. Arana, J. Holboell, ‘Switching Operation Simulations In A Large Offshore Wind Farm With Use Of Parametric Variation And Frequency Domain Severity Factor’, in Proceedings of UPEC 2012: 47th International Universities’ Power Engineering Conference, London, 2012

[3]I. Arana, "Switching overvoltages in off-shore wind power grids. Measurements, modelling and validation in time and frequency domain." *PhD Dissertation,Technical University of Denmark,* 2011.

[4] A. Holdyk, B. Gustavsen, I. Arana, J. Holboell, ‘Wide Band Modeling of Power Transformers Using Commercial sFRA Equipment’. Submitted to IEEE Transactions on Power Delivery.